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Utilization of Variable Emissivity Electrochromic Devices for Space Suit Thermal Control

Christopher J. Massina, James A.
Nabity, David M. Klaus
*Aerospace Engineering Sciences
University of Colorado Boulder*



University of Colorado
Boulder



Abstract

Motivation

Evaluate **the full suit, variable emissivity radiator** architecture's potential for **reducing the consumable burden** associated to current **EVA thermal control** mechanisms

Purpose

Present an **overview of work completed** to address these needs, and collect feedback where appropriate

Results

Provide first-order environmental and operational guidelines for future consideration

Future Work

Complete remaining thermal vacuum assessment and compile work into dissertation





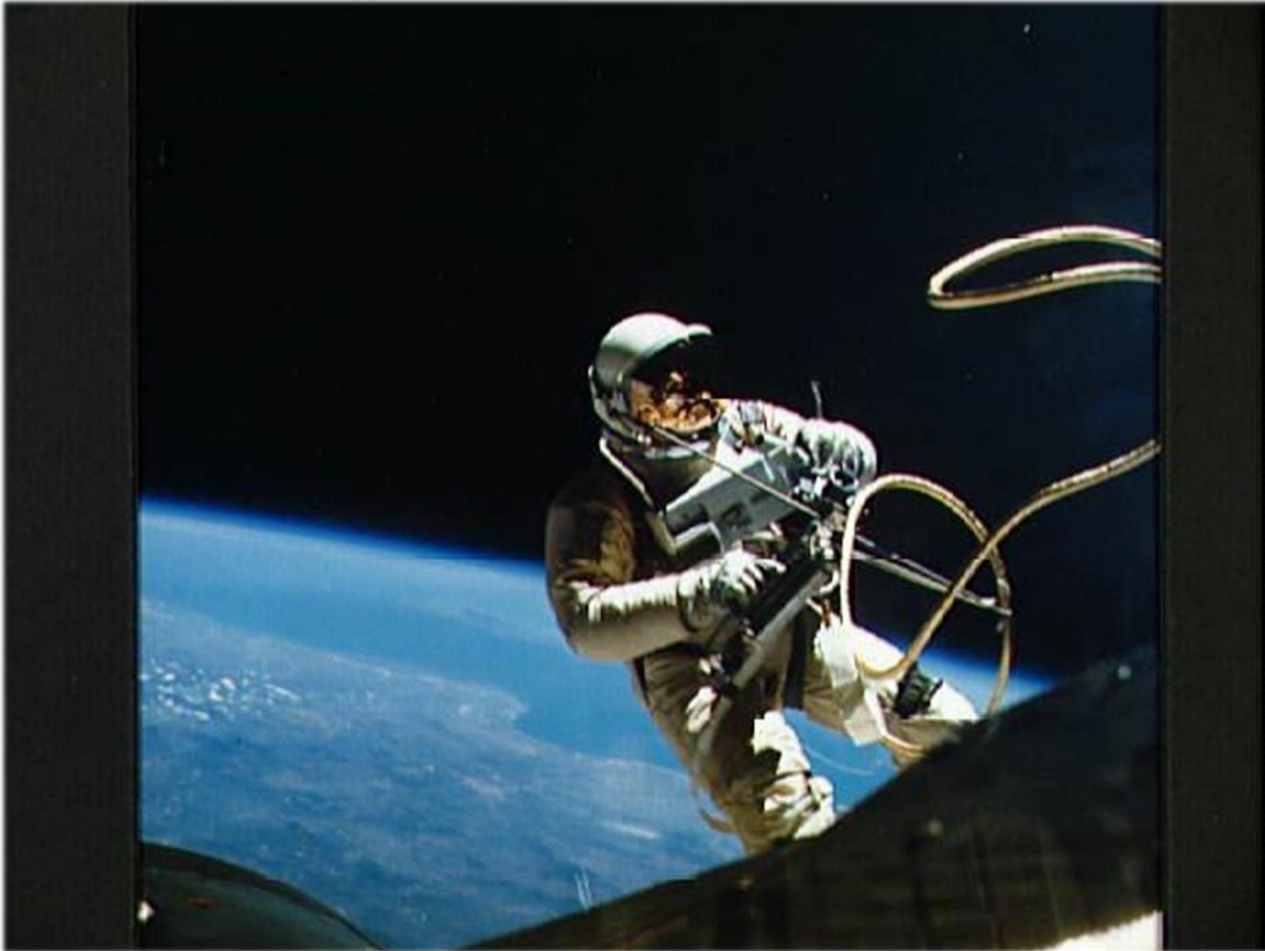
Introduction - Fundamental Premise

- The space suit must provide the ability to “**support human life and enable functionality** [within working environment]” [Klaus et al., 2006]
- In terms of thermal – system must **maintain the astronaut’s core temperature** to the appropriate level to **avoid impaired physical and mental performance** [Buckey, 2006]





Ed White, Gemini 4



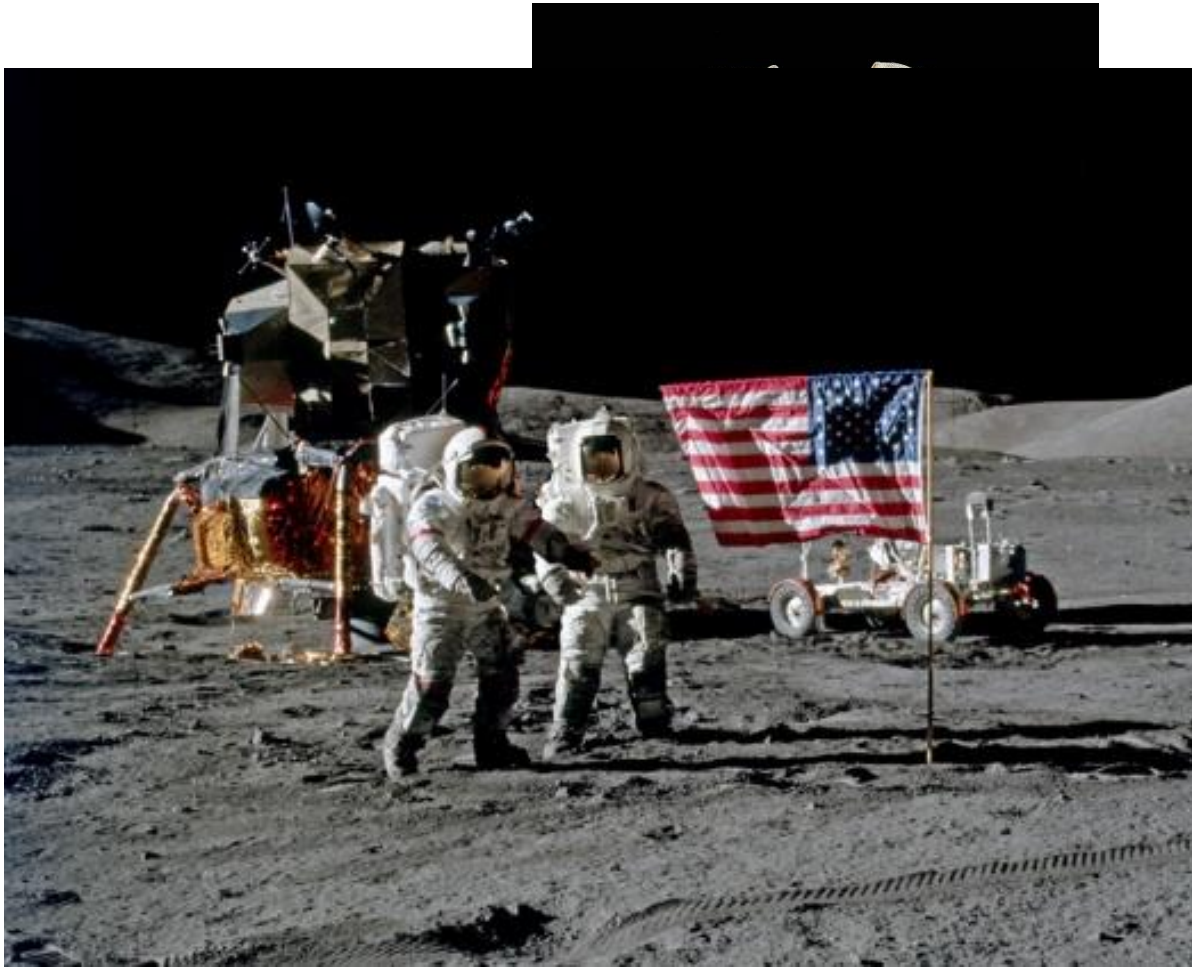


Apollo LCG





Gene Cernan & Harrison Schmitt, Apollo 17





Sublimator Drawbacks

- Impacts to transport and logistics [Eckart, 1996]
 - ~**3.6 kg** of **water lost** per EVA [Nabity et al., 2007; Bue et al., 2013]
- Environment **contamination concerns**
 - Sensitive hardware – Hubble [Hedgeland et al., 1994]
 - Forward contamination of solar system bodies [Race et al., 2003; Conley and Rummel, 2008; Conley and Rummel, 2010]
- Performance **degradation** over time [Birur & Westheimer, 2007; Leimkuehler & Stephan, 2008; Sheth et al., 2012]
- Potential alternative thermal control method
 - Use the majority of a **space suit's surface area as a radiator**
 - Proposed as early as 1965 for LEO [Richardson, 1965]
 - Elaborated upon in the Chameleon Suit [Hodgson, 2001; Hodgson et al., 2004]
 - Consideration of **electrochromic devices** to modulate dissipation potential [Metts, 2010; Metts et al., 2011]





Research Objectives Overview

- Investigate a potential space suit thermal control technology for closed-loop (non-venting) operations
- **Proposed architecture: full suit flexible radiator with variable infrared electrochromic surfaces**
 - Environment Characterization
 - Integration Architecture
 - Control Approach
- Results provide **expanded operational and integration requirements** (guidelines) from previous investigations





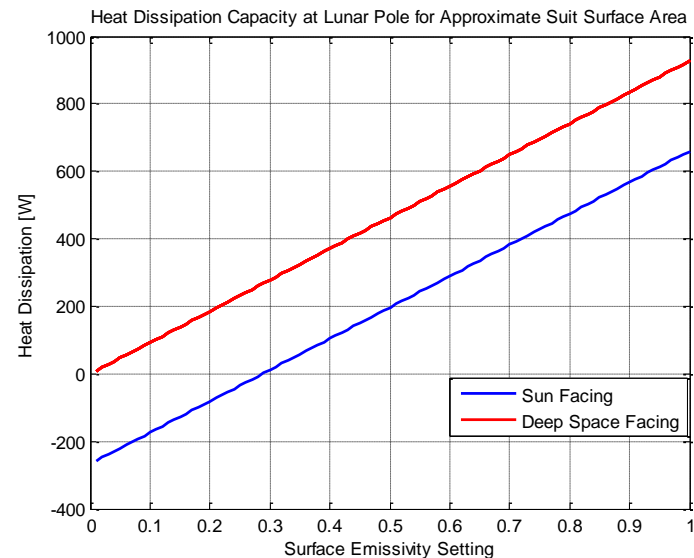
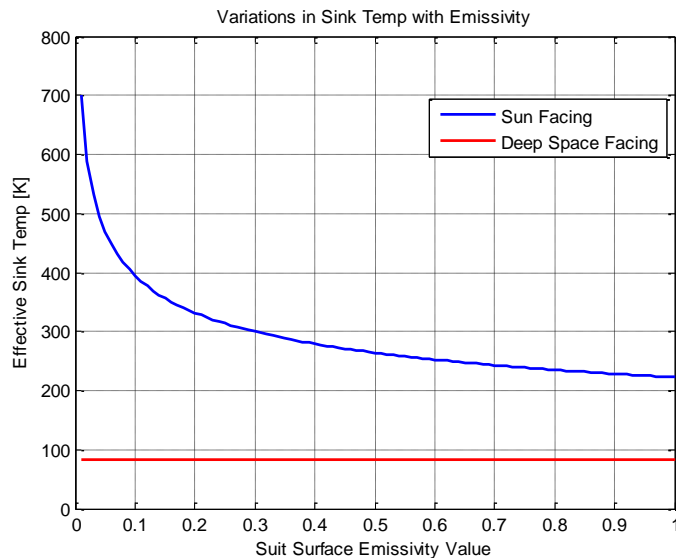
INDIVIDUAL ASSESSMENTS





Emissivity Impact on Performance Potential

- In otherwise static environment determine how **sink temperature** varies with changes in emissivity when radiator has a non-zero solar absorptivity
 - Evaluation of variable heat dissipation capacity variation at **lunar pole** with variations in radiator emissivity.
 - Established that an emissivity range of **0.3-0.8** is capable of providing **~275-1100 W** of heat dissipation.



Citation:

Massina, C.J. and Klaus, D. M. (2013). *Considerations for Incorporating Variable Emissivity Radiators into a Space Suit Heat Rejection System.* (Poster) 43rd International Conference on Environmental Systems, Vail, CO.





Lunar Environment Suit Interaction

- **Static** suit surface properties
- Suit approximated as a **flat plate**
 - **Equal area** division where one side shades the other from the direct solar component
 - Assume **infinite plane** lunar surface in local EVA environment (e.g. featureless)
 - **View Factor** (VF) for either radiator area is **0.5** to both the lunar surface and space environment

- **Equation set for evaluations:**

- Incident solar flux (S) of $1368 \text{ W}/\text{m}^2$ [Gilmore, 2002]
- Lunar surface solar absorptivity (α_{Lunar}) of 0.92
- Angle from subsolar (θ)

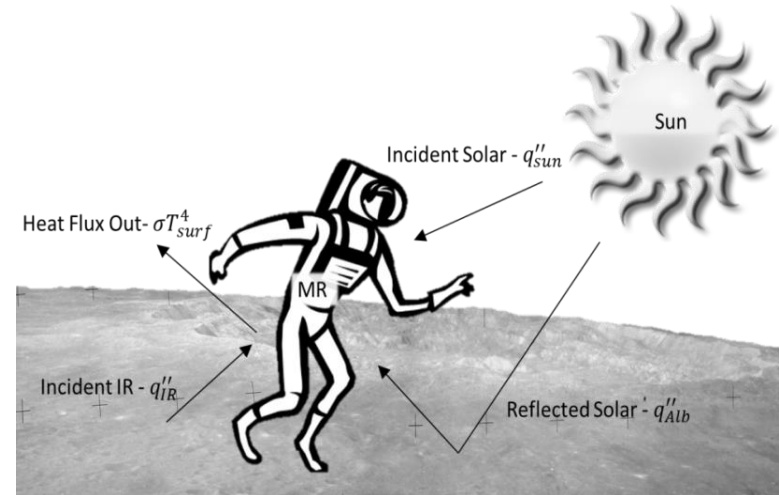
$$q''_{IR} = \cos\theta * VF * S \alpha_{Lunar}$$

$$q''_{sun} = VF * S \text{ or } 0$$

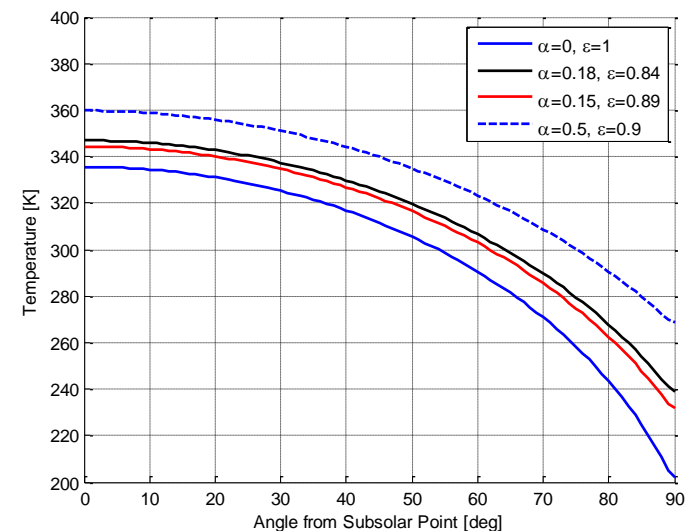
$$q''_{Alb} = \cos\theta * VF * S (1 - \alpha_{Lunar})$$

$$q''_{rad} = \epsilon(\sigma \bar{T}_{surf}^4 - q''_{IR}) - \alpha(q''_{sun} + q''_{Alb})$$

$$q_{rad} = \sum \frac{A}{2} q''_{rad} = \frac{A}{2} (2\epsilon(\sigma \bar{T}_{surf}^4 - q''_{IR}) - \alpha(q''_{sun} + 2q''_{Alb}))$$



Radiative Heat Fluxes During Lunar EVA



Temperature requirements for 300W dissipation with gas pressure suit area

Define q_{rad} and solve for \bar{T}_{surf}

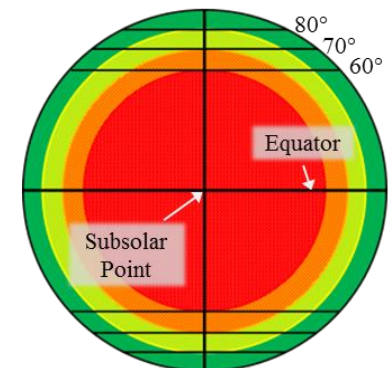


Lunar Environment Impact on Utilization

- Define radiator **surface temperature guidelines** for desired amount of heat dissipation on the lunar surface for radiator with static surface properties
 - Characterize baseline radiator temperature to dissipate 300 W and 700 W of heat on lunar surface using the full suit flexible radiator concept
 - Black Body: $\alpha = 0, \epsilon = 1$; EMU: $\alpha = 0.18, \epsilon = 0.84$; Degraded: $\alpha = 0.5, \epsilon = 0.9$
 - Identify **threshold latitudes** for long duration mission sites
 - Can be used to characterize allowable **thermal resistance**

Threshold angles from subsolar point for 310 K and 290 K mean radiator surface temperatures.

	Blackbody 310 K	Blackbody 290 K	EMU 310 K	EMU 290 K	Degraded 310 K	Degraded 290 K
EMU Area 300 W Rejection	46°	60°	58°	70°	69°	80°
EMU Area 700 W Rejection	60°	72°	72°	83°	81°	DNE
MCP-Suit Area 300 W Rejection	57°	70°	69°	80°	79°	90°
MCP-Suit Area 700 W Rejection	81°	DNE	DNE	DNE	DNE	DNE



Exploration restriction with angle from subsolar point. 300 W of dissipation, EMU area at 290 K.

Citation:

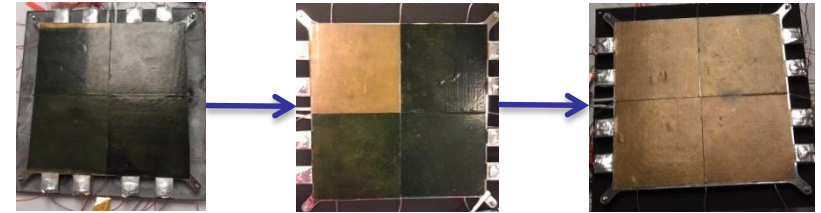
Massina, C.J., Klaus, D.M., and Sheth, R.B. (2014). *Evaluation of Heat Transfer Strategies to Incorporate a Full Suit Flexible Radiator for Thermal Control in Space Suits*. ICES-2014-089.



Pixel Integration Concept & Considerations



Jade Suit Integration, Image Credit: www.theguardian.com



Individual Electrochromic Activation

- Need to define pixel area and corresponding number of pixels
- Electrochromic control modes: **continuously variable** vs. **high-low state mixing**
- Radiator integration modes: **constant temperature** (dual-loop) vs. **constant flux** (uniform heat leak)



First-Order Pixel Area Determination

- Used a cylindrical space suit approximation in a lunar pole environment
- Key Results
 - Constant Temperature
 - Either **1 or ~48 individual pixels** depending on control mode
 - Required emissivity variation of **0.169 to 0.495**
 - Constant Flux
 - **~400 individual pixels** in continuously variable emissivity control
 - No transverse conduction within suit walls considered
 - Required emissivity variation of **0.122 to 0.967**
 - Should consider these values to be a minimum baseline as more complex geometries will generally require additional pixelation

Citation:

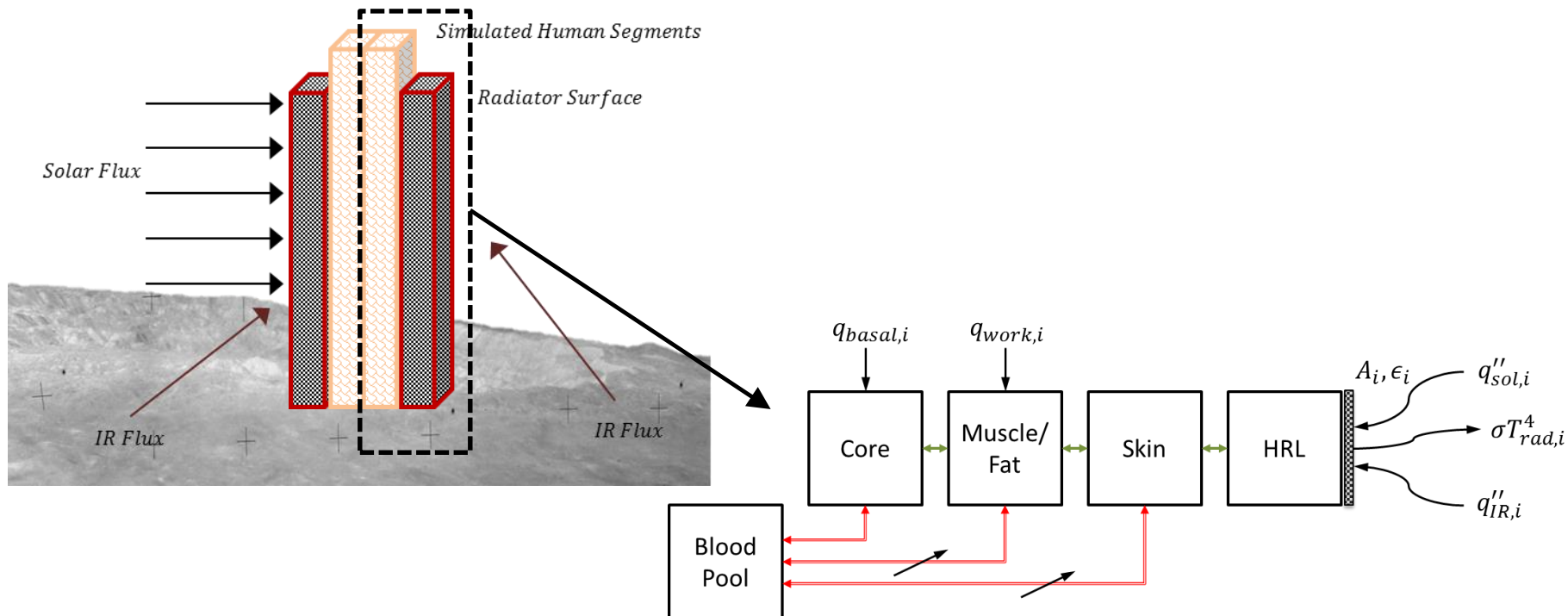
Massina, C.J., and Klaus, D.M. (2015). *Defining a Discretized Space Suit Surface Radiator with Variable Emissivity Properties*. Journal of Thermal Science and Engineering Applications. [accepted]





Dynamic System Model

- Constructed simplified 7-node human metabolic model based on previous work [Crawford et al., 2000; Campbell et al., 2000; Montgomery, 1974; Stolwijk and Hardy, 1966]
- Model allows for asymmetric external environment exposure to a two-sided radiator approximation





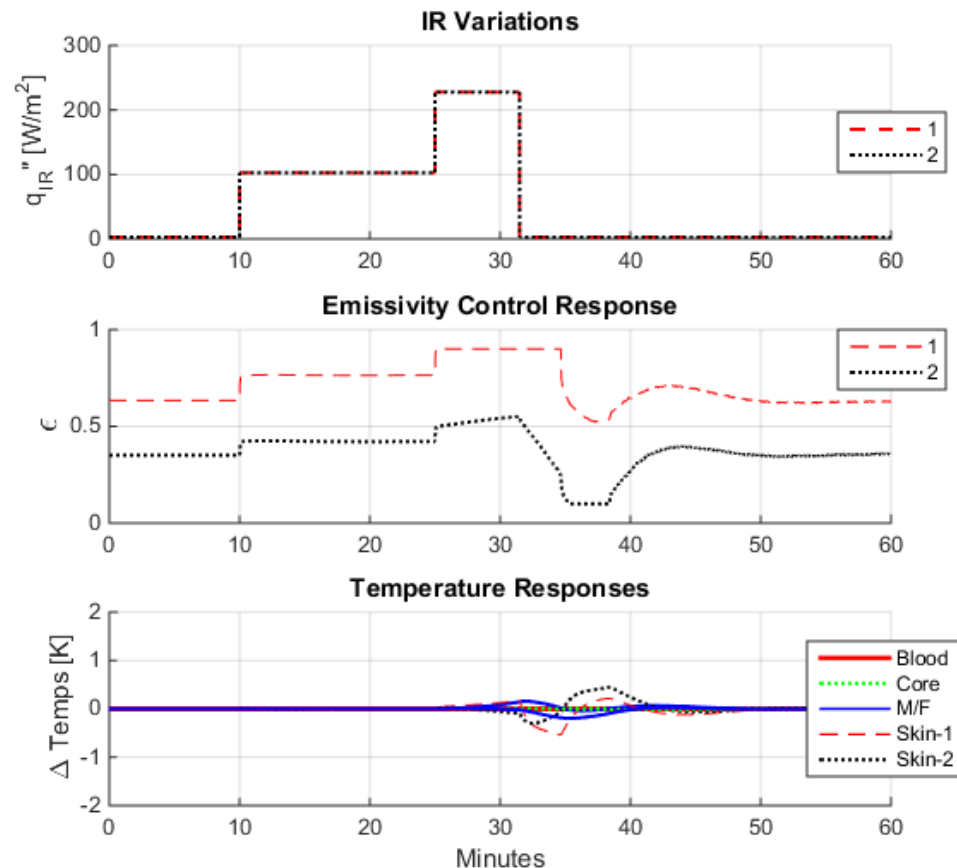
Dynamic Modeling Output

Example Environment Variation

Profile

- Bulk variations in incident IR flux
 - Step increase of 100 W/m^2 at 10 min.
 - Additional step increase of 125 W/m^2 at 25 min.
 - Return to nominal condition at 31 min

This variation is consistent with bulk flux changes that may be experienced when entering a surface region with complex geometries (boulder, etc.)





Dynamic Modeling Discussion

- 4 test scenarios were completed: 2 metabolic variations and 2 environment variations
- Emissivity saturation shown to have a negative impact on the simulated human's thermal condition
 - Short excursions can be compensated for by the system
 - Prolonged exposure can cause the model to diverge (instabilities)
- Nature of current model dictated that **little or no variation in BHS** is experienced before the system diverges
 - Current output does not map one-to-one with NASA HIDH
 - No excursion into potential dangerous regimes

Citation:

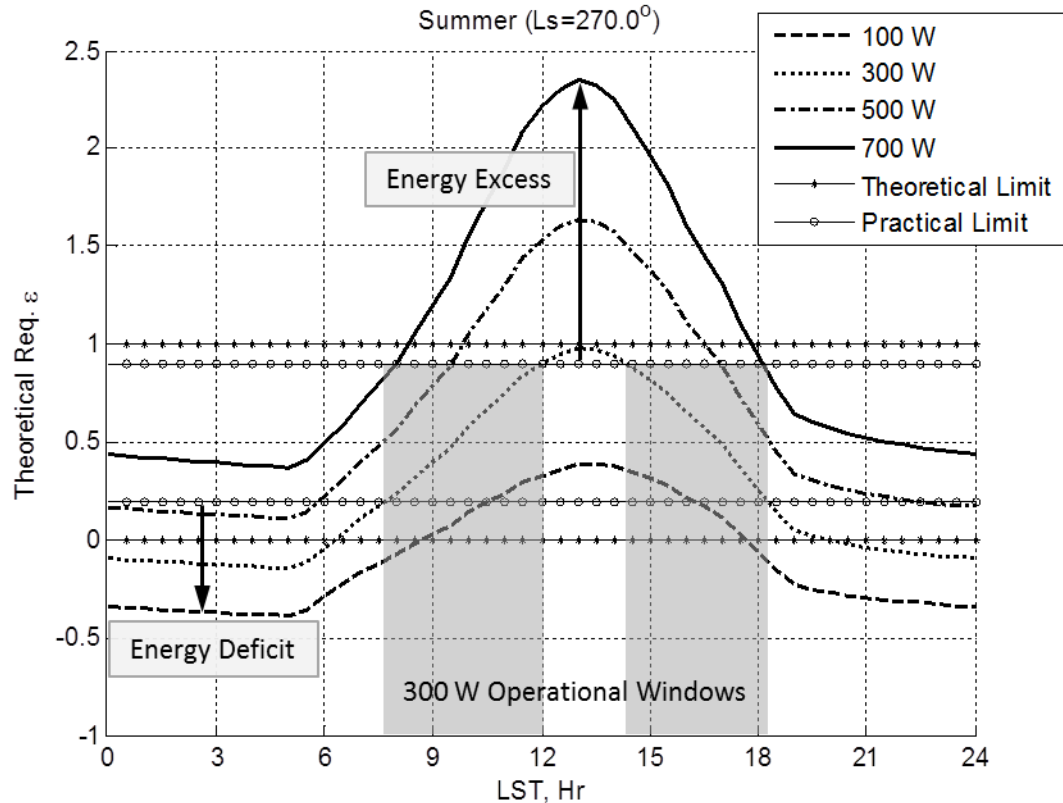
Massina, C.J., Nabity, J.A., and Klaus, D.M. (2014). *Modeling the Human Thermal Balance in a Space Suit using a Full Surface, Variable Emissivity Radiator*. ICES-2015-026.





Martian Surface EVA Extension

- Examined diurnal variations in external environment for 4 seasons at **27.5 °S** latitude
- Considered variations in wind speed, absorptivity, and area
- Seasonal supplemental thermal control guidelines identified
 - Limit **heater capacity: 631 W**
 - Limit additional **dissipation capacity: 1423 W**



Diurnal theoretical emissivity values for summer conditions
and sustained wind speed of 15 m/s

Citation:

Massina, C.J., and Klaus, D.M. (20YY). *Prospects and Environmental Characteristics for Variable Emissivity Thermal Control of Space Suits on the Martian Surface*. Advances in Space Research. [In Prep]





ONGOING & FUTURE WORK



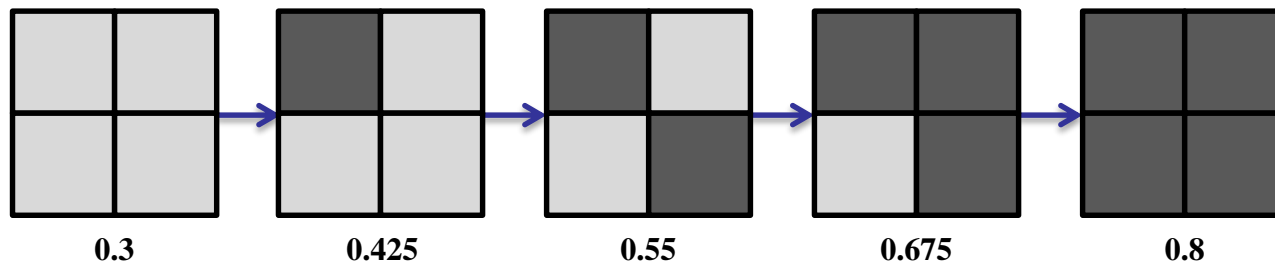


Mixed Emissivity Verification in Thermal Vac

- **Assess feasibility** and assumption quality for constant temperature and uniform flux integration
- Demonstrate **impacts of high-low emissivity state mixing** on thermal performance
 - Thermal vacuum, at CU
 - Test article is under construction and testing is to occur Fall 2015



JSC Electrochromic Test Article





Key Points for Further Elaboration

- Dynamic model expansion in fidelity and test scenarios
 - Use or expansion of 41-node metabolic man or Wissler models for asymmetric environments
 - Use more realistic working environment fluxes [Hager et al., 2015]
- Further definition of external environment restrictions for using the architecture
- Parametric definition of heat removal layer properties for maintaining thermal equilibrium
- Construction of an integrated test article for further testing and concept verification





CONCLUSIONS





Summary

- *Analytically and empirically evaluated the potential to achieve closed-loop EVA thermal control by integrating variable IR emissivity electrochromics into a full suit flexible radiator thermal control architecture*
- *Provided a robust mechanism for assessing integration feasibility*
- *Defined heat transport properties and requirements for supplemental heat rejection systems*
- *The scope of this work is very much inline with NASA's EVA systems technology development goals*





Conclusions

- The full suit radiator with variable emissivity surfaces architecture has proven to be **feasible** for several environments, at the level of the investigations
- Outputs could be used to for operations planning and determination of integration requirements
- Results suggest that a hybrid thermal control system is required to expand EVA operational regimes
- Suggest that additional work be completed in physical device development so further integrated testing can be completed





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QUESTIONS

